



Brief communication: Sankey diagrams of the simulated mass balance of sea ice and its overlying snow cover across both hemispheres

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Abstract. The mass budget of sea ice and its overlying snow cover integrates the thermodynamic and dynamic processes that govern their variability. Here we investigate how Sankey flow diagrams, a widely used and intuitive data visualisation technique for integrated budgets, can provide insight into sea ice and snow-on-ice mass budgets. We draw on multiple model sources, including fully coupled climate models and an ERA5-forced ocean–sea ice reanalysis. The sea ice and snow-on-sea-ice budget terms are defined following established Coupled Model Intercomparison Project protocols, area-integrated over the Northern and Southern Hemispheres for a prescribed modern-era climatological period (2015 to 2034), and displayed as flows whose width is proportional to the annual mass flux. The sources and sinks are labelled by their percentage contribution to the total budget, including the ensemble spread of each relative term. Both the climate model ensemble and the reanalysis show a similar relative budget partitioning, an encouraging sign of reliability in our budget estimates. Overall, we find the diagrams provide an accessible, process-level reference for understanding and visualizing the sea ice and snow mass budgets. The framework we provide is intended as a living resource that can be extended with additional climate simulation output (e.g. the upcoming CMIP7 release) and ocean-sea ice reanalyses, as well as suggested changes in Sankey configuration (or alternative visualization approaches) to emphasize different aspects of the mass budgets. This work has been undertaken in support of the IPCC Seventh Assessment Report (AR7).



1 Introduction

Sea ice is a central component of the polar climate system and a key indicator of global climate change (Notz et al., 2016; Fox-Kemper et al., 2021). Its evolution is controlled by the competing effects of various thermodynamic growth and melt mechanisms and the dynamic redistribution of ice and its overlying snow cover. Although the large-scale decline of Arctic sea ice and the more complex behavior of Antarctic sea ice are relatively well documented (Notz and Stroeve, 2016; Parkinson, 2019; Fox-Kemper et al., 2021), global climate models continue to exhibit wide spread in sea ice in terms of mean state, variability and trends (Massonnet et al., 2018; Notz and SIMIP Community, 2020; Roach et al., 2020). The underlying mass budgets, comprised of the individual sources and sinks that sum to the net change in ice and snow mass, offer a process-level route to understanding this model spread. Multi-model budget assessments have been undertaken as far back as the Coupled Model Intercomparison Project phase 3 (CMIP3; Holland et al., 2010), although these efforts have been sporadic and non-exhaustive. In the lead-up to the CMIP6 data release, the Sea Ice Model Intercomparison Project (SIMIP) provided a community request for a standardized set of mass-tendency variables (Notz et al., 2016), enabling a more consistent, process-level budget analyses, which has subsequently been undertaken comprehensively for the Arctic (Keen and Blockley, 2018; Keen et al., 2021) and the Antarctic (Li et al., 2021).

A complementary development within terrestrial glaciology has come from the ice sheet community, where Mankoff et al. (2025) presented gross ice-sheet mass flows and their constituent terms as intuitive flow (Sankey) diagrams. The technique dates back to one of its first published applications by Kennedy and Sankey (1898), who used a flow diagram to depict the energy losses of a steam engine, and remains widely used across disciplines, from science and engineering to economics, e.g. the International Energy Agency uses Sankey diagrams to visualise national energy balances from supply through to final consumption (International Energy Agency, 2026). Such diagrams place all budget components on a common footing and make the relative magnitude of each flux immediately visible. To our knowledge, Sankey diagrams have not been applied to sea ice and snow-on-sea-ice mass budgets to-date. While ice-sheet diagrams were largely designed on the available observational synthesis of the constituent terms, this approach cannot be readily applied to sea ice, as observation-based, spatially complete sources for the individual sea ice mass-budget fluxes do not currently exist. In this context, simulation output remains the primary means of quantifying a closed sea ice and snow mass budget. Field campaigns and autonomous platforms, in particular the ice mass balance buoy (IMB) network (e.g. West et al., 2019; West and Blockley, 2025) offer a route towards observational constraints on some of these terms via updated process understanding, and integrating such data is a key direction for future work. However, such field campaigns do not allow for a comprehensive, year-round and basin-scale assessment of processes governing sea ice and snow mass change. Satellite-derived estimates now provide an observationally constrained, year-round Arctic sea-ice volume budget at basin scale (Heorton et al., 2025), but they do not resolve the individual thermodynamic mass-budget terms needed for a process-level Sankey diagram, nor do they extend to the Southern Ocean or the snow-on-sea-ice budgets.

Motivated by the ice sheet Sankey effort from Mankoff et al. (2025) and in support of the IPCC Seventh Assessment Report (AR7), here we test and describe analogous Sankey diagrams for the sea ice and snow-on-ice mass budgets of a subset of



CMIP6-class models and a single atmosphere-forced sea ice reanalysis simulation. This effort grew directly out of discussions between AR7 chapter authors and the SIMIP community on how best to communicate the simulated sea ice mass budget in an accessible, process-oriented way. Our goals here are twofold: (1) to provide a first look at how Sankey diagrams can be developed and serve as a useful tool for visualising the sea ice and snow mass budgets; and (2) to examine how models represent the individual budget terms, and in particular the substantial differences simulated between the Northern and Southern hemispheres.

This brief communication documents how the diagrams are produced and presents the multi-model ensemble (MME) mean budgets for both hemispheres. To ensure our workflow is fully reproducible, we provide an accompanying open source GitHub repository (<https://github.com/cjcardinale/sea-ice-mass-balance>) containing the processing code and Jupyter Notebooks that generate the Sankey diagrams, along with further detail on the models and mass-budget variables currently available (Sect. 5). The diagrams are not intended as an observationally-constrained assessment; rather, they are a reference visualisation that can be updated as further simulations, e.g. upcoming CMIP7 data, and observational constraints are added.

2 Data and methods

2.1 Models and simulations

Here we use output from ten CMIP6 models and the Community Earth System Model Large Ensemble (CESM2-LE). The models were prioritized primarily by the availability of CMIP6 mass-budget outputs needed to construct the Sankey diagrams (Sect. 2.2). In addition, we use the CESM2 Large Ensemble (Rodgers et al., 2021) instead of the original CMIP6 CESM2 contribution as it provides 50 ensemble members, and fixed an existing issue with the output snow-ice budget terms in the original CESM2 (and CESM2-WACCM) outputs. Budgets are computed using the ScenarioMIP SSP2-4.5 projection output (O'Neill et al., 2016) over a 2015–2034 climatological window, averaged across all available ensemble members for each model. CESM2-LE is only available during this window with the SSP3-70 scenario forcing, but atmospheric carbon dioxide concentrations and resulting global mean temperatures are only thought to notably diverge after our study period (O'Neill et al., 2016). We secondarily prioritized the inclusion of models based on their performance in a recent plausibility assessment (Petty et al., 2025) where the models used here generally show plausible mean (2018–2025) states relative to satellite-derived sea ice area, total freeboard and winter Arctic sea ice thickness estimates and rank highly compared to other CMIP6 models, as summarized further in the GitHub repository.

In addition to the fully coupled models, we include a sea ice only mass budget assessment using output from an ERA5-forced (Hersbach et al., 2020) global ocean–sea ice simulation using NEMO4–SI3 (the successor to the LIM model; Vancoppenolle et al., 2023) at $1/4^\circ$ nominal horizontal resolution over the period 2000 to 2024 (Richaud et al., 2026a). The output follows the same CMIP6/SIMIP conventions plus the addition of a porous ridging ice mass gain term not provided in the CMIP6 models (described in Sect. 2.2.1), with the data publicly available on Zenodo (Richaud et al., 2026b).

The twelve models analyzed here, along with their associated sea ice model component, number of ensemble members and availability of mass budget outputs are summarized in Table 1. Sea ice model diversity remains limited: six simulations use



Table 1. Models, ensemble sizes, and diagnostic availability. All simulations provide the standard ice-budget, snowfall, and snowmelt terms as described in Sect. 2.2, with exceptions and snow budget additions listed in the notes. Mems. is the number of ensemble members common to the seven thermodynamic ice-budget diagnostics over 2015–2034.

Model or simulation	Sea ice model	Mems.	Notes
<i>Coupled models</i>			
Australian Community Climate and Earth System Simulator – Climate Model version 2 (ACCESS-CM2; Bi et al., 2020)	CICE5.1.2	10	inc. snow-to-ice, snow dyn..
Community Earth System Model version 2 Large Ensemble (CESM2-LE; Rodgers et al., 2021)	CICE5.1.2	50	inc. snow-to-ice, snow dyn., and vap. exch..
Whole Atmosphere Community Climate Model configuration of CESM2 (CESM2-WACCM; Gettelman et al., 2019)	CICE5.1.2	5	inc. snow vap. exch..
CNRM Climate Model version 6.1 (CNRM-CM6-1; Voltaire et al., 2019)	GELATO6.1	1	inc. snow-to-ice, snow dyn., and vap. exch..
CNRM Earth System Model version 2.1 (CNRM-ESM2-1; Séférian et al., 2019)	GELATO6.1	1	inc. snow-to-ice, snow dyn., and vap. exch..
EC-Earth version 3 (EC-Earth3; Döscher et al., 2022)	LIM3	20	inc. snow-to-ice, snow dyn., and vap. exch.; lateral melt and dynamics not archived/available.
Hadley Centre Global Environment Model version 3, Global Coupled configuration 3.1, Low Resolution (HadGEM3-GC31-LL; Kuhlbrodt et al., 2018)	CICE5.1.2	5	inc. snow-to-ice and snow dyn..
Institut Pierre-Simon Laplace Climate Model version 6A, Low Resolution (IPSL-CM6A-LR; Boucher et al., 2020)	LIM3	11	inc. snow-to-ice, snow dyn., and vap. exch.; lateral melt not archived and dynamics excluded (includes porous ridging term).
Meteorological Research Institute Earth System Model version 2.0 (MRI-ESM2-0; Yukimoto et al., 2019)	MRI.COM4.4	5	inc. snow-to-ice, snow dyn., and vap. exch. Ice dynamics excluded (anomalous residual).
Norwegian Earth System Model version 2, Low Resolution (NorESM2-LM; Seland et al., 2020)	CICE5.1.2	14	inc. snow-to-ice and wind drift.
UK Earth System Model version 1.0, Low Resolution (UKESM1-0-LL; Sellar et al., 2019)	CICE5.1.2	4	inc. snow-to-ice and snow dyn. vap. exch..
<i>Atmosphere-forced model</i>			
NEMO-SI3 ocean-sea ice, ERA5-forced (NEMO4–SI3; Vancoppenolle et al., 2023; Richaud et al., 2026a)	SI3	1	inc. snow-to-ice, snow dyn., and vap. exch.. For ice also inc. porous ridging.



CICE5.1.2, two use LIM3 (EC-Earth3 and IPSL-CM6A-LR), two use GELATO6.1, and one uses MRI.COM4.4. A similar low sea ice model diversity was noted in Keen et al. (2021) despite their use of a larger model subset. In addition, several models share the same atmosphere or ocean model component. Regardless, we hope to simplify the inclusion of additional model outputs and enhanced model diversity in follow-up efforts through our inclusion of analysis code/notebooks.

2.2 Budget variables

Budget terms follow the SIMIP definitions for the sea ice and snow on sea ice mass tendencies (Notz et al., 2016). We summarise below the processes as implemented in typical CMIP6-class sea ice models, drawing on available sea ice model documentation (Hunke et al., 2015; Vancoppenolle et al., 2012) and thus update the definitions in Notz et al. (2016) where appropriate. The exact formulations can vary between models and model versions as discussed in Keen et al. (2021), which we also aim to make clear in the relevant subsections below. In addition, the availability of these variables differs between models and is summarised for the twelve models used here in Table 1. The full CMIP6 archive output availability through the Earth System Grid Federation (ESGF), is provided on our GitHub (<https://github.com/cjcardinale/sea-ice-mass-balance>), which also includes the various post-processing steps required to ensure output is consistent with the SIMIP definitions/units across all models. Note also that some of these variable names are changing for CMIP7 (<https://wcrp-cmip.org/cmip-phases/cmip7/cmip7-data-request/>) which we identify in the relevant subsection headers below.

We present the ice and snow budgets separately for clarity, but note that they are physically coupled through snow-to-ice conversion and that one could consider a combined snow+ice budget. All CMIP6 models represent sea ice mass as ice volume multiplied by a constant bulk ice density. Brine and gas inclusions do not explicitly contribute to the reported mass, even in models that represent brine (e.g. through mushy-layer or prognostic-salinity schemes).

2.2.1 Sea ice mass sources

Basal growth (`sidmassgrowthbot`) represents the vertical thickening of existing ice at its base. This occurs when the conductive heat flux through the ice exceeds the ocean-to-ice heat flux such that seawater freezes onto the ice bottom (also called congelation growth).

Open water ice production (`sidmassgrowthwat`) represents the formation of new ice in open water. The volume of new ice is derived from the ocean surface heat loss and is typically added over the open-water fraction of the cell assuming some initial thickness to calculate the areal fraction of new ice (see next paragraph). As such, this term represents new-ice creation rather than thickening of existing ice. This term is sometimes labelled “frazil” (following the SIMIP shorthand for “growth in supercooled open water”), but most models do not explicitly resolve frazil-crystal dynamics and instead simply diagnose new-ice formation over the open-water fraction from the surface heat loss.

Importantly, the split between open water production and basal growth is largely a model-parameterization dependent classification rather than a physical distinction, as it hinges on each model’s prescribed thickness of new ice. If that value is small, a given volume of new ice covers a larger area, open water closes more rapidly, and subsequent growth is preferentially diagnosed as basal (congelation) growth; if it is large, open water persists longer and the contribution of new-ice formation increases. This



thickness ranges from 0 to ~10 cm across CMIP6 models (most use 5 cm), such that models with a zero value report almost no open-water production while those with a 10 cm value report roughly double the amount from models using 5 cm (Keen et al., 2021). Due to the somewhat subjective definitions of the boundary between the basal growth and open water ice production terms, we also combine those two into a secondary “Ocean Growth” node in the Sankey diagram (see below).

120 **Snow-to-ice conversion** (CMIP6: `sidmassssi`, `sidmassgrowthsi` in CMIP7) represents snow-ice formation that occurs when a heavy snow load depresses the snow-ice interface below sea level. Seawater then floods and refreezes in the submerged snow pack, effectively converting snow into sea ice, thus contributing a source of ice mass. Note that this is distinct from superimposed ice, in which slush, developing due to water from surface snowmelt or rain, refreezes at the snow-ice interface, which is not included in any of the models featured here. The associated snow-mass loss is described separately in
 125 Sect. 2.3.1.

Porous ridging term represents ice formation when seawater trapped between ice blocks in newly formed pressure ridges freezes. Unlike the mechanical ridging, which redistributes existing ice (described below in the sea ice dynamics term), this process transfers mass from the ocean to the ice and can therefore contribute to the hemispheric ice mass budget. This process is unique to our forced NEMO4-SI3 simulation (Vancoppenolle et al., 2023; Richaud et al., 2026a). Note that this term is also
 130 included in the IPSL-CM6A-LR model, but is combined with transport/advection into an aggregated dynamics term which we do not include in this study to avoid inconsistencies with other model definitions.

2.2.2 Sea ice mass sinks

Top melt (`sidmassmeltp`) represents melt at the upper ice surface when the net surface energy balance is positive (surface held at the melting point, with excess energy melting snow first and then ice. This term thus only contributes to sea ice
 135 mass loss in the absence of an overlying snow layer).

Basal melt (`sidmassmeltp`) represents melt at the ice base when the ocean heat flux exceeds the conductive flux into the ice.

Lateral melt (CMIP6: `sidmasslat`, `sidmassmeltp` in CMIP7) represents melting of the vertical sides of ice floes, parameterised typically through a prescribed melt rate based on ocean surface temperature and an assumed floe size and shape.

140 As in the growth terms, basal and lateral melt are grouped into a secondary “Ocean Melt” node, as these represent melt based on similar ice-ocean energy imbalance, such that increases in lateral melt typically result in decreases to basal melt and the distinction is currently largely model-dependent.

Surface vapour exchange over sea ice (`sidmassevapsubl`) represents sea-ice mass exchange with the atmosphere through evaporation or sublimation (mass loss) and vapour deposition (mass gain). It is the only thermodynamic term that can
 145 contribute either an ice mass loss or gain and is typically set to zero in the presence of a snow layer (see snow term below).

2.3 Snow on sea ice mass sources

Snowfall (CMIP6: `sndmasssnf`, `sisndmasssnf` in CMIP7) represents solid precipitation onto the ice and is the primary source of snow on sea ice.



2.3.1 Snow on sea ice mass sinks

150 **Snowmelt** (CMIP6: `sndmassmelt`, `sisndmasssnf` in CMIP7) represents ablation of the snow pack when the net surface energy balance is positive. Snow is melted preferentially before the underlying ice. Most of this melt water generally enters the ocean, although melt ponds (if represented) can delay this through meltwater pooling.

Snow-to-ice conversion (CMIP6: `sndmasssi`, `sisndmasssi` in CMIP7) represents the loss of snow mass during the flooding and snow-ice formation process described in Sect. 2.2.1. This snow-on-sea-ice mass sink is not necessarily equal to
 155 the sea ice mass gain term. Some models form snow ice by effectively compressing snow to the density of sea ice, so the two terms balance. Others include seawater in the mass budget, with seawater supplying about two thirds of the new sea ice mass; in that case the ice-mass gain is about three times the snow-on-sea-ice mass loss.

Wind drift (CMIP6: `sndmasswindrif`, `sisndmasswind` in CMIP7) represents the loss of blowing snow from the ice into the ocean. This is not commonly parameterized in CMIP-class models (indeed only NorESM2-LM of the investigated
 160 models includes this variable and provides the output).

Surface vapour exchange over snow-on-sea-ice (CMIP6: `sndmasssubl`, `sisndmasssubl` in CMIP7) represents snow-mass loss through sublimation or gain through vapour deposition. As in the equivalent ice term, this the only term that can contribute either a snow mass loss or gain.

2.4 Sea ice and snow dynamics

165 **Sea ice dynamics** (CMIP6: `sidmassdyn`) represents the local ice mass tendency due to horizontal transport and mechanical redistribution. Conventional, non-porous ridging and rafting redistribute ice across thickness categories but conserve total ice mass. Consequently, `sidmassdyn` should make no net contribution when integrated over an entire hemisphere, apart from numerical or diagnostic residuals. Over a constrained regional domain, however, it can represent net ice import or export across the boundaries.

170 **Snow dynamics** (CMIP6: `sndmassdyn`, `sisndmassdyn` in CMIP7) represents the corresponding local snow-mass tendency associated with transport by the drifting sea ice. Its conservative transport component likewise integrates to zero over an effectively closed domain. In some models, however, the diagnostic also includes snow removed during mechanical redistribution. For example, the standard CICE5 configuration retains 50 % of the snow on ice participating in ridging and transfers the remainder to the ocean (Hunke et al., 2015). The snow-dynamics term can thus contribute a non-zero contribution to the
 175 hemispheric snow budget even without transport across a domain boundary.

2.5 Flux calculations and Sankey diagram construction

Fluxes are area-integrated over the Northern and Southern Hemispheres, which are then referred to as Arctic and Antarctic estimates herein. In addition, we include an example for a more constrained Inner Arctic Ocean (IAO) domain, defined using the combined Central Arctic, Beaufort Sea, Chukchi Sea, E. Siberian Sea, Kara Sea and the Barents Sea taken from the National
 180 Snow and Ice Data Center Arctic regional mask (National Snow and Ice Data Center, 2021). This follows the same regional



masking approach of the Keen et al. (2021) CMIP6 mass balance assessment and provides insight into the contribution of dynamics (snow and ice export out of the Arctic).

Each per-area flux ($\text{kg m}^{-2} \text{s}^{-1}$) is multiplied by the native model grid-cell area and summed over the domain to give a total mass flux in Gt yr^{-1} . Using monthly data, we first form an annual sum for each calendar year, then average those annual totals over 2015–2034 for each ensemble member, and finally average across the available ensemble members of each model. All available members are then treated equally when forming the multi-model ensemble (MME) mean, so models that provide larger ensembles (in particular CESM2-LE, but also EC-Earth3, NorESM2-LM and IPSL-CM6A-LR) contribute more weight than the single-member models. An alternative would be to calculate individual model means prior to generating the multi-model mean, or retain only one member from each model, giving each model equal influence (as in Notz and SIMIP Community (2020)); we did not do so, in order to increase the number of members used in this analysis and to provide a more complete estimate of uncertainty. Before integration, several models require corrections to enforce a common sign convention (losses negative, gains positive) and a common area basis (per grid-cell rather than per sea-ice area) which are documented in the GitHub repository (Sect. 5). Finally, with the time-mean ensemble-mean budget terms, we compute percentages for each sink term relative to the total sinks (and each source term relative to the total sources).

For each hemisphere, the integrated fluxes are incorporated into a Sankey diagram (Figs. 1–2), with ribbon width proportional to the annual mass flux. Sources enter the central reservoir (sea ice or snow) from the left and sinks leave to the right. A small “residual” flow closes the budget where sources and sinks do not exactly balance, which is expected to reflect primarily the overall mean mass tendency over our study period. The Sankey ribbon widths are normalized across both hemispheres (we divide all terms across both diagrams by the largest term available in either diagram, 21,401 Gt/yr for ice and 4,8201 Gt/yr for snow, absolute mass budget terms are provided in the GitHub) so that the ribbon widths can be compared visually across both hemispheres. Each flow is then labelled by its percentage contribution to either the source or sink totals, which we consider the most robust way to present the terms given the model uncertainties discussed above; the accompanying notebook (Sect. 5) includes the option to label the flows with absolute fluxes (Gt yr^{-1}) instead. The figures also include a reference scale bar (10,000 Gt yr^{-1} for sea ice and 2,000 Gt yr^{-1} for snow-on-sea-ice) to help visualize the absolute quantities. Ensemble spread is shown as a range on each term’s percentage contribution, obtained by varying that term across the available ensemble members while holding all other terms fixed at their MME-mean values. Ensemble spread is shown as a percentage range on each budget term label, obtained by varying that term across the available ensemble members while holding all other terms fixed at their MME-mean values. The intra-ensemble spread in just the CESM2-LE output (not shown) is much smaller than the multi-model range, indicating that the label ranges are dominated by inter-model differences rather than intra-model internal variability.

The diagrams are rendered with the `plotly` Python library (Plotly Technologies Inc., 2015); a Jupyter notebook that reproduces them, together with an up-to-date list of the available models and variables, is included in the GitHub repository (Sect. 5).



3 Results

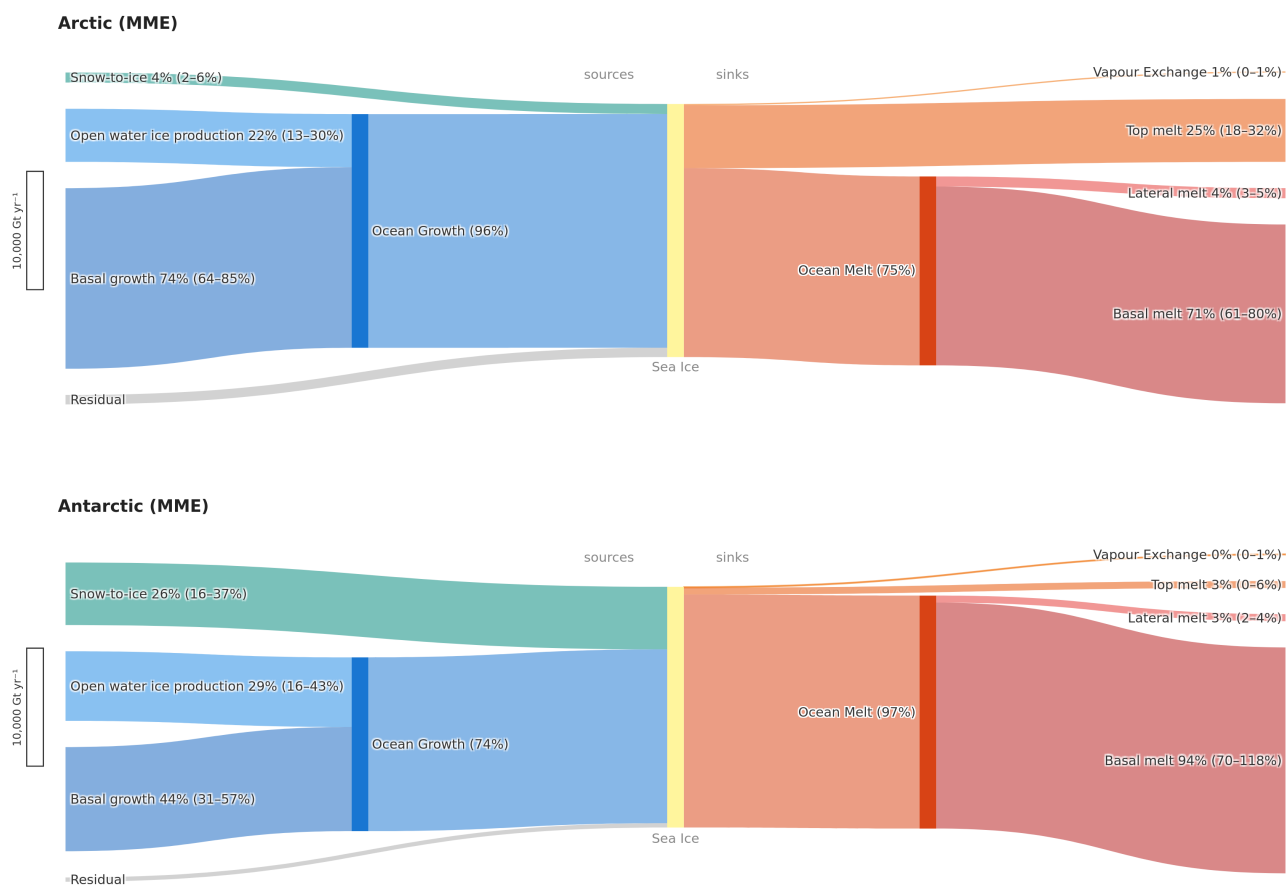


Figure 1. Multi-model ensemble (MME) mean **sea ice** mass budget for (top) the Arctic and (bottom) the Antarctic, 2015–2034. Ribbon width is proportional to the annual mass flux (Gt yr^{-1}); sources enter the central sea-ice reservoir from the left and sinks leave to the right, with thermodynamic terms grouped into “Ocean Growth” and “Ocean Melt” nodes. Flux widths are normalized across both hemispheres consistently (we divide all terms across both diagrams by the largest term available in either diagram). Node labels give each term’s MME-mean % share of its side’s total, together with the range that share would span if that term were varied across the available ensemble members while all other terms were held at their MME-mean contribution. The white scale bar on the left can be used to convert each term to an absolute quantity in Gt yr^{-1} .

215 In both hemispheres, the MME-mean sea ice mass budget (Fig. 1) is, to first order, a balance between thermodynamic growth and thermodynamic melt, with basal (congelation) growth the largest single source and basal melt the largest single sink. A sea ice dynamic term does not appear in the hemispheric-scale Sankey diagrams since the dynamics reorganizes the mass



distribution locally (Sect. 2.4). It is included in the snow diagrams as several models permit snow to be lost through ridging, contributing a net sink even at hemisphere-scales. The snow budgets (Fig. 2) are, unsurprisingly, dominated by snowfall as the primary mass source. Because the diagrams each share a common flux normalization (the sea ice and snow figures are normalized separately), the significantly higher Antarctic snowfall relative to all other snow mass terms is directly apparent. These hemispheric-wide, annual mean results, mask the significant underlying seasonal and regional variability, as well as the contribution of dynamics at more regional scales.

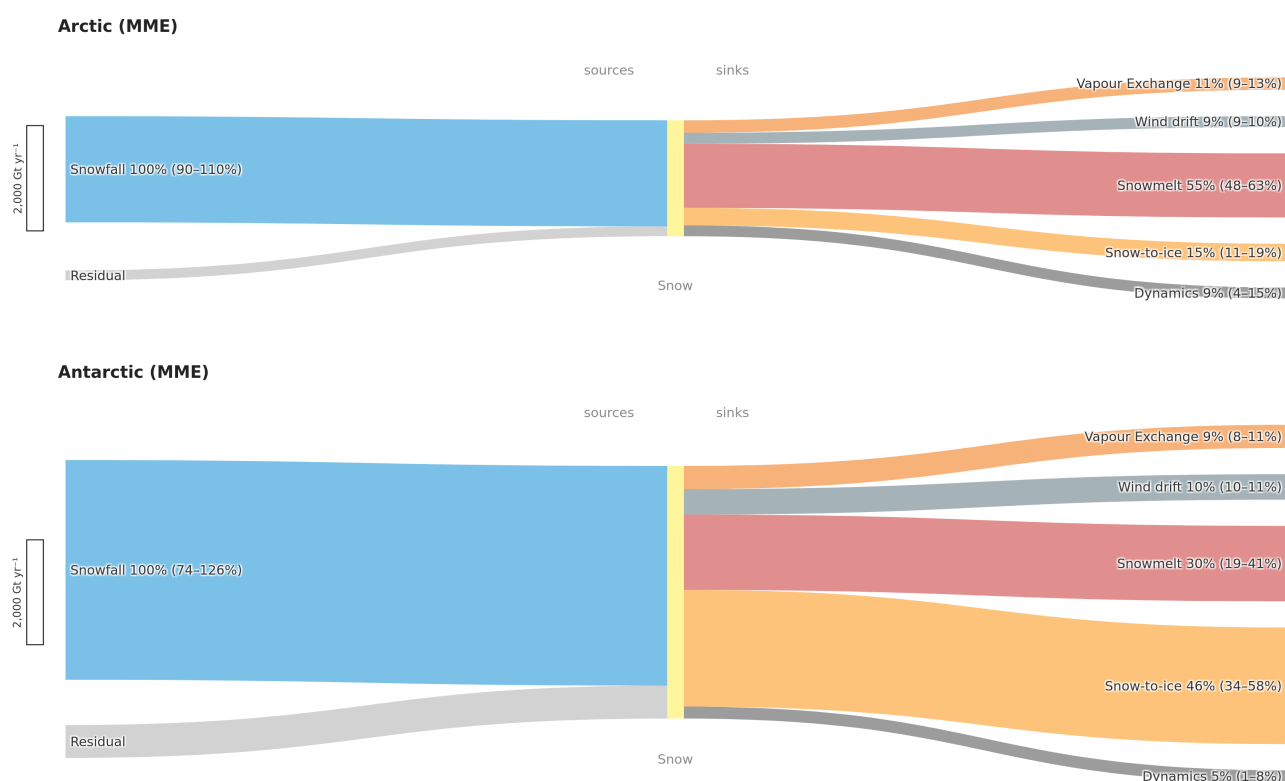
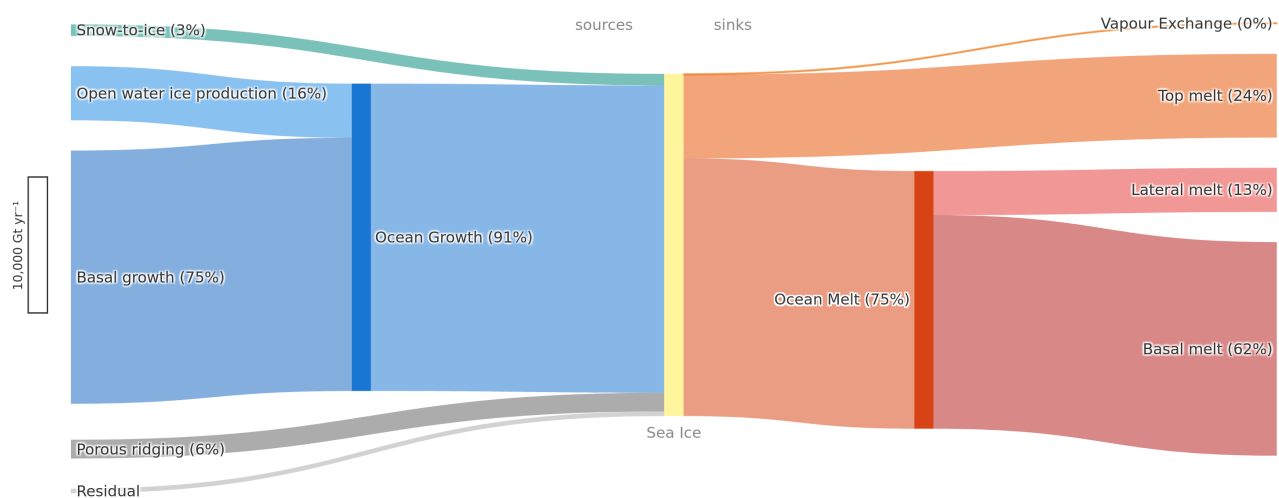
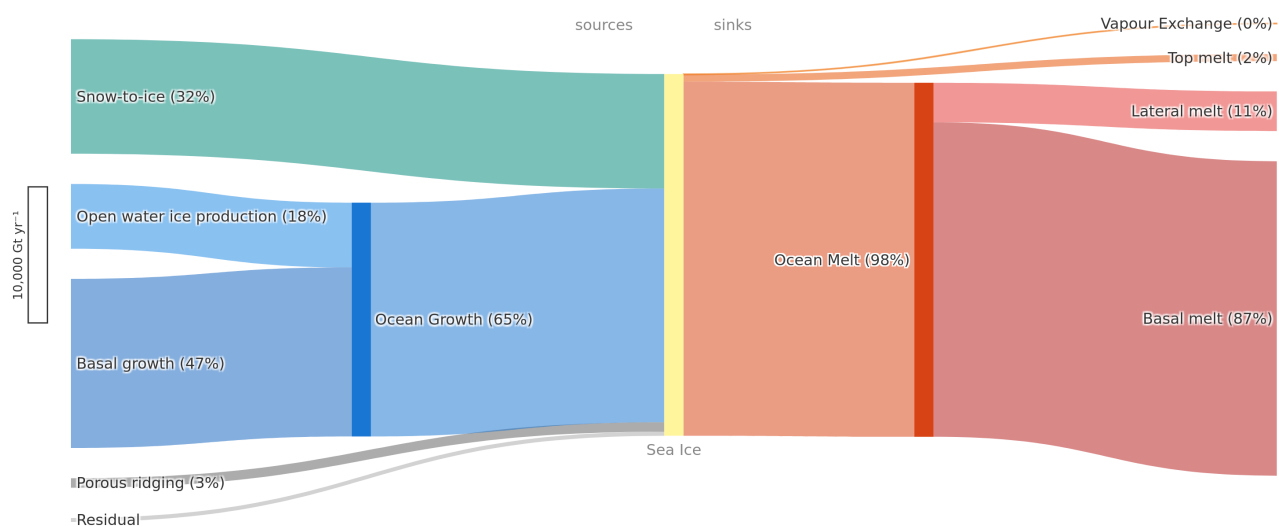


Figure 2. As Fig. 1, but for the MME-mean **snow on sea ice** mass budget. Flux widths are again normalized consistently across both hemispheres.

In addition to these shared hemispheric features, a few first-order contrasts stand out in the percentages (quoted next to each term; Figs. 1–2) of the total sources or sinks within a budget. (i) Snow-to-ice conversion is a large Antarctic sea ice source but minor in the Arctic: conversion of snow into sea ice accounts for $\sim 26\%$ of sea ice formation in the Antarctic versus $\sim 4\%$ in the Arctic, alluding to a central role of snow-ice (flooding) formation in the Antarctic budget. Arctic ice growth is instead dominated by basal (congelation) growth ($\sim 74\%$ versus $\sim 44\%$ of sources), while the Antarctic has proportionally larger open-water-production ($\sim 29\%$ versus $\sim 22\%$) and snow-ice contributions. (ii) Surface (top) melt is a major Arctic sea



Antarctic (ERA5-forced NEMO-SI3)





ice mass sink but essentially absent in the Antarctic: top melt accounts for $\sim 25\%$ of Arctic sea ice loss but only $\sim 3\%$ in the Antarctic, where ice loss is almost entirely basal ($\sim 94\%$ basal melt, versus $\sim 68\%$ in the Arctic). This near-absence of top ice melt does not imply an absence of surface melting: models melt snow preferentially, so a thicker, more persistent Antarctic snow cover (Fig. 2) routes surface ablation into snowmelt rather than top ice melt. (iii) Antarctic snow is lost mainly through snow-to-ice conversion ($\sim 46\%$ of snow sinks, versus $\sim 30\%$ snowmelt), whereas in the Arctic snow melt dominates ($\sim 55\%$) and snow-to-ice conversion is comparatively small ($\sim 15\%$).

The remaining terms – lateral melt, evaporation/sublimation, snow wind drift, the dynamics/export residual, and the partitioning of open water production versus basal growth (Sect. 2.2.1) – are secondary in magnitude. We also attach lower confidence to them, in the sense that they are less consistently available or defined across the ensemble (Table 1), more sensitive to parametrization choices, and in some cases provided by only one or a few models (e.g. wind drift from NorESM2-LM only). The open-water versus basal-growth split is a particularly clear example: it is controlled largely by the prescribed thickness of new ice rather than by a distinct physical process (Sect. 2.2.1). More generally, the ratio of ensemble spread to the MME contribution is indicative of confidence in each term: a small ratio implies that models largely agree on that contribution, whereas a large ratio implies that the quoted budget term share is poorly constrained by the models. Arctic basal growth and basal melt have a lower ratio compared to the other terms and could therefore be considered higher-confidence, with the caveat again that these are still model-based estimates. A more systematic, IPCC-style confidence assessment is discussed in Sect. 4.

The ERA5-forced NEMO4–SI3 simulation (Fig. 3) shows a remarkably similar relative budget to the CMIP6 MME (Fig. 1), with the same dominant terms and hemispheric contrasts despite an observationally constrained atmosphere versus free-running coupled models and a different sea ice component. In the Arctic, NEMO4–SI3 partitions ice growth into $\sim 75\%$ basal growth and $\sim 16\%$ open water production and ice loss into $\sim 62\%$ basal and $\sim 24\%$ top melt; in the Southern Ocean snow-to-ice conversion ($\sim 32\%$) is again a major source and basal melt ($\sim 87\%$) dominates the loss, closely matching the coupled-model percentages above. One difference is that NEMO4–SI3 reports a porous-ridging growth term explicitly (Sect. 2.2.1), a small but distinct ice source ($\sim 6\%$ in the Arctic and $\sim 3\%$ in the Antarctic) that the coupled models do not account for. Using Sankey diagrams to compare these sources does, however, require explicit choices. In Fig. 3 we keep the MME hemisphere-wide ribbon normalization so that flux magnitudes can be compared by eye, while the percentage labels use this simulation’s own source and sink totals. We can see that despite the similar relative split, the ERA5-forced simulation shows a higher total mass reservoir compared to the CMIP6 MME. One could instead normalize each diagram independently, which would emphasise relative partitioning, or drop the shared scale altogether, which would emphasise mean-state biases that are larger in the un-normalized fluxes.

To highlight the inclusion of a dynamic ice export term explicitly, we additionally calculate these budgets within a constrained inner-Arctic-Ocean domain (Fig. 4). In this budget, net dynamical ice export accounts for approximately 10% of the total mass loss, making it secondary to thermodynamic melt but nevertheless a substantial component of the regional budget. Because the Inner Arctic Ocean Sankey ribbons retain the normalization used in our full Arctic results, their widths provide a basic visual comparison of flux magnitudes between the two domains. The percentage labels, however, have different domain-specific denominators and should not be compared directly.



265 Keen et al. (2021) adopted this approach for their CMIP6 Arctic sea ice mass budget, computing budgets over an Arctic Ocean basin domain, where the net advection of ice across its boundary (dominated by export through the Fram Strait) contributed significantly (9–30 % of the total annual ice loss). The approach translates less directly to the Southern Ocean, which lacks a confining basin or coastline, but a latitude- or sector-limited domain could serve a similar purpose (Richaud et al., 2026a).

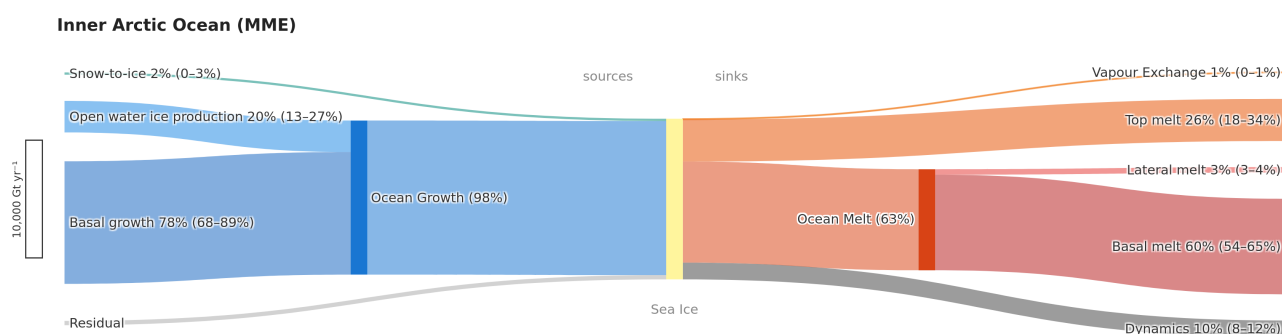


Figure 4. As in Fig. 1, but calculated over an Inner Arctic Ocean domain. This version includes an explicit ice advection/export term, alongside the thermodynamic sources and sinks, complementing the hemispheric budget in Fig. 1 (see Sect. 2.4). Budget percentage contributions are calculated relative to the total sources or sinks within this Inner Arctic Ocean budget, whereas ribbon widths retain the normalization used in Fig. 1, permitting comparison of flux magnitudes on a common scale.

270 4 Discussion

Several caveats apply to the results presented in this Brief Communication. The budgets are generated from model output only and are not observationally-constrained, although the models used here generally show plausible mean states across multiple metrics (Petty et al., 2025). The ensemble we use here is relatively small (eleven coupled models plus one forced simulation) and is primarily used as a first-order example of how to construct Sankey diagrams and visualize budget differences across hemispheres. Because all ensemble members are treated equally, models with larger ensembles contribute more weight to the MME and to the label ranges; using a single member per model would equalise model influence but would reduce the sample.

275 The much smaller CESM2-LE intra-ensemble spread relative to the multi-model range indicates that most of the spread is still inter-model.

The snow budgets are considered more uncertain than the ice budgets owing to inconsistent and incomplete snow flux output across models, e.g. wind drift is only provided by the NorESM2 (Table 1). The snow wind-drift term represents snow blown off the ice and lost to the ocean, so, in contrast to other dynamics terms, is a genuine sink from the snow budget even at regional scales, however the inclusion of this parameterization is missing from the majority of CMIP-class models. Open water ice production (“frazil”) diagnostics are computed inconsistently across models and warrant further investigation. The remaining

280



secondary terms identified in Sect. 3 (lateral melt, surface vapour exchange, snow wind drift, the mean mass tendency residual, and the partitioning of open-water production versus basal growth) should likewise be interpreted cautiously.

An important next step, and one already established practice in the ice-sheet community, is to attach a level of confidence to each term to guide interpretation, including for IPCC-level assessment (an expected utility of these diagrams). The ratio of ensemble spread to the MME contribution provides a first-order guide to model confidence: a small ratio implies higher inter-model agreement/internal variability, whereas a large ratio implies low agreement and lower confidence. Arctic basal growth and basal melt terms show notably lower ratios and could therefore be considered higher-confidence terms. Because CESM2-LE internal spread is much smaller than the multi-model range, those label ranges mainly reflect inter-model disagreement rather than intra-model variability. This is still only a model-only diagnostic of agreement, not a full confidence assessment: it does not capture missing physics, incomplete output, or the lack of observational constraints. Most other terms would presently be assigned *low* confidence, consistent with Li et al. (2021), who found Antarctic inter-model spread of the same order as the multi-model mean, especially in snow-ice, basal-melt and top-melt. A systematic assessment, ideally distinguishing absolute fluxes from relative shares and anchored to observational benchmarks such as the satellite-derived Arctic volume budget of Heorton et al. (2025) and the IMB-based flux evaluation of West and Blockley (2025), remains a priority for future work.

The exercise of visualising these budget terms increases the need to reassess some of the established SIMIP labels and conventions. The open water ice production (new-ice formation) term (`sidmassgrowthwat`), referred to in Notz et al. (2016) as “frazil” is a good example: as noted above, it is better understood in our view as the parameterization of open water ice production (new-ice formation) of various young ice types, e.g. pancake ice, than as explicit frazil-crystal formation. As these diagnostics move from a specialist model-intercomparison context towards wider use in assessments such as AR7, clearer and more physically transparent naming would help non-specialist users interpret the terms correctly.

Finally, we note that Sankey diagrams are only one of several ways these budgets could be communicated, and a bar chart of the same integrated fluxes would arguably convey similar information (as used in, e.g., Keen et al., 2021; Li et al., 2021). Whatever the format, the normalization should be adapted to the objective of the figure: a shared scale across hemispheres, as used here, simplifies comparisons between the relative budgets of each hemisphere; independent per-diagram normalization emphasises the internal partitioning of a single budget; and un-normalized fluxes emphasise differences in absolute magnitude, for example between periods, regions, ice versus snow, or a forced simulation and the coupled MME. Additional options to explore include grouped or stacked bar charts (which more readily accommodate inter-model spread and uncertainty ranges), seasonal-cycle decompositions of each term rather than annual integrals, spatial maps of the dominant local source and sink terms, spatial maps showing the net transfers of mass between regions, and interactive versions of the diagrams (which `plotly` supports natively) allowing users to toggle between models, hemispheres, percentages and absolute fluxes. We encourage community feedback and discussion on which of these approaches would be most useful and worth pursuing in future model assessment efforts.



5 Conclusions

We have presented a compact set of Sankey diagrams that summarise the sea ice and snow-on-ice mass budgets of current CMIP6-class models, following the constituent-flux visualisation recently adopted for ice sheets (Mankoff et al., 2025) and building on the SIMIP mass-budget framework and assessments (Notz et al., 2016; Keen et al., 2021). The budgets shown here are derived entirely from model simulations. They illustrate how the models represent these fluxes and should not be interpreted as an observed budget. Nevertheless, the coupled models and the forced simulation show similar first-order hemispheric contrasts in the relative budgets: Arctic ice growth is more basal-dominated than the Antarctic, Arctic ice loss includes a larger top-melt share, and snow-to-ice conversion plays a larger role in the Antarctic ice and snow budgets. These contrasts should be read as features of the simulated budgets. The ratio of ensemble spread to the MME contribution offers a first guide to confidence: Arctic basal growth and basal melt have a low ratio and can be treated as higher-confidence terms, whereas most other terms – and the snow-ice terms in particular – remain highly uncertain given incomplete snow budget outputs and large inter-model spread.

The diagrams are intended as a living, openly available reference that can be updated as new data and approaches are made available. Planned extensions include adding further CMIP6 models, incorporating CMIP7 output as it becomes available, additional forced ocean–sea ice simulations building on the ERA5-forced comparison presented here (Fig. 3), and observational constraints from field campaigns and buoy networks (West et al., 2019; West and Blockley, 2025). Overall, we hope these diagrams provide an accessible entry point to the simulated polar sea ice and snow mass budgets in support of AR7.

Code availability. The processing code and a Jupyter notebook that computes the budgets and generates the Sankey diagrams with the `plotly` Python library (Plotly Technologies Inc., 2015), along with individual model versions and up-to-date documentation of the available models and mass-budget variables, are openly available at <https://github.com/cjcardinale/sea-ice-mass-balance> (a Zenodo archived version DOI to be added on release).

Data availability. CMIP6 model output was primarily accessed from Earth System Grid Federation (ESGF) data nodes, using the `intake-esgf` Python package (developed under the ESGF2-US project) to search and download native-grid SIMON variables for each model. Where available, cloud-hosted datasets (e.g., <https://cmip6-pds.s3.amazonaws.com/pangeo-cmip6.json>) were accessed using the `intake-esm` Python package. CESM2 Large Ensemble (CESM2-LE) data are publicly available from the NCAR Geoscience Data Exchange (GDEX; dataset d651056, <https://gdex.ucar.edu/datasets/d651056/>); for computational efficiency, data were accessed via NCAR campaign storage on the glade filesystem. More information on data access is available at <https://github.com/cjcardinale/sea-ice-mass-balance>. The ERA5-forced NEMO4–SI3 ice mass fluxes are available on Zenodo (<https://doi.org/10.5281/zenodo.18347836>; Richaud et al., 2026b).

Competing interests. At least one of the (co-)authors is a member of the editorial board of "The Cryosphere"



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350 References

- Bi, D., Dix, M., Marsland, S., O'Farrell, S., Sullivan, A., Bodman, R., Law, R., Harman, I., Srbinovsky, J., Rashid, H. A., Dobrohotoff, P., Mackallah, C., Yan, H., Hirst, A., Savita, A., Dias, F. B., Woodhouse, M., Fiedler, R., and Heerdegen, A.: Configuration and spin-up of ACCESS-CM2, the new generation Australian Community Climate and Earth System Simulator Coupled Model, *Journal of Southern Hemisphere Earth Systems Science*, 70, 225–251, <https://doi.org/10.1071/ES19040>, 2020.
- 355 Boucher, O., Servonnat, J., Albright, A. L., Aumont, O., Balkanski, Y., Bastrikov, V., Bekki, S., Bonnet, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Caubel, A., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., D'Andrea, F., Davini, P., de Lavergne, C., Denvil, S., Deshayes, J., Devilliers, M., Ducharne, A., Dufresne, J.-L., Dupont, E., Éthé, C., Fairhead, L., Falletti, L., Flavoni, S., Foujols, M.-A., Gardoll, S., Gastineau, G., Ghattas, J., Grandpeix, J.-Y., Guenet, B., Guez, L. E., Guilyardi, E., Guimberteau, M., Hauglustaine, D., Hourdin, F., Idelkadi, A., Joussaume, S., Kageyama, M., Khodri, M., Krinner, G., Lebas, N., Levavasseur, G., Lévy, C., Li, L., Lott, F., Lurton, T., Luyssaert, S., Madec, G., Madeleine, J.-B., Maignan, F., Marchand, M., Marti, O., Mellul, L., Meurdesoif, Y., Mignot, J., Musat, I., Ottlé, C., Peylin, P., Planton, Y., Polcher, J., Rio, C., Rochetin, N., Rousset, C., Sepulchre, P., Sima, A., Swingedouw, D., Thiéblemont, R., Traore, A. K., Vancoppenolle, M., Vial, J., Vialard, J., Viovy, N., and Vuichard, N.: Presentation and evaluation of the IPSL-CM6A-LR climate model, *Journal of Advances in Modeling Earth Systems*, 12, e2019MS002010, <https://doi.org/10.1029/2019MS002010>, 2020.
- 360 Döscher, R., Acosta, M., Alessandri, A., Anthoni, P., Arsouze, T., Bergman, T., Bernardello, R., Boussetta, S., Caron, L.-P., Carver, G., Castrillo, M., Catalano, F., Cvijanovic, I., Davini, P., Dekker, E., Doblas-Reyes, F. J., Docquier, D., Echevarria, P., Fladrich, U., Fuentes-Franco, R., Gröger, M., v. Hardenberg, J., Hieronymus, J., Karami, M. P., Keskinen, J.-P., Koenigk, T., Makkonen, R., Massonnet, F., Ménégos, M., Miller, P. A., Moreno-Chamarro, E., Nieradzick, L., van Noije, T., Nolan, P., O'Donnell, D., Ollinaho, P., van den Oord, G., Ortega, P., Prims, O. T., Ramos, A., Reerink, T., Rousset, C., Ruprich-Robert, Y., Le Sager, P., Schmith, T., Schrödner, R., Serva, F., Sicardi, V., Sloth Madsen, M., Smith, B., Tian, T., Tourigny, E., Uotila, P., Vancoppenolle, M., Wang, S., Wärlind, D., Willén, U., Wyser, K., Yang, S., Yepes-Arbós, X., and Zhang, Q.: The EC-Earth3 Earth system model for the Coupled Model Intercomparison Project 6, *Geoscientific Model Development*, 15, 2973–3020, <https://doi.org/10.5194/gmd-15-2973-2022>, 2022.
- 370 Fox-Kemper, B., Hewitt, H. T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S. S., Edwards, T. L., Gollidge, N. R., Hemer, M., Kopp, R. E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I. S., Ruiz, L., Sallée, J.-B., Slangen, A. B. A., and Yu, Y.: Ocean, Cryosphere and Sea Level Change, in: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 1211–1362, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, <https://doi.org/10.1017/9781009157896.011>, 2021.
- Gettelman, A., Mills, M. J., Kinnison, D. E., Garcia, R. R., Smith, A. K., Marsh, D. R., Tilmes, S., Vitt, F., Bardeen, C. G., McInerney, J., Liu, H.-L., Solomon, S. C., Polvani, L. M., Emmons, L. K., Lamarque, J.-F., Richter, J. H., Glanville, A. S., Bacmeister, J. T., Phillips, A. S., Neale, R. B., Simpson, I. R., DuVivier, A. K., Hodzic, A., and Randel, W. J.: The Whole Atmosphere Community Climate Model Version 6 (WACCM6), *Journal of Geophysical Research: Atmospheres*, 124, 12 380–12 403, <https://doi.org/10.1029/2019JD030943>, 2019.
- 380 Heorton, H., Tsamados, M., Landy, J., and Holland, P. R.: Observationally constrained estimates of the annual Arctic sea-ice volume budget 2010–2022, *Annals of Glaciology*, 66, e9, <https://doi.org/10.1017/aog.2025.3>, 2025.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Vil-



- laume, S., and Thépaut, J.-N.: The ERA5 global reanalysis, *Quarterly Journal of the Royal Meteorological Society*, 146, 1999–2049, <https://doi.org/10.1002/qj.3803>, 2020.
- Holland, M. M., Serreze, M. C., and Stroeve, J.: The sea ice mass budget of the Arctic and its future change as simulated by coupled climate
 390 models, *Climate Dynamics*, 34, 185–200, <https://doi.org/10.1007/s00382-008-0493-4>, 2010.
- Hunke, E. C., Lipscomb, W. H., Turner, A. K., Jeffery, N., and Elliott, S.: CICE: the Los Alamos Sea Ice Model Documentation and Software
 User's Manual Version 5.1, Tech. Rep. LA-CC-06-012, Los Alamos National Laboratory, <https://doi.org/10.5281/zenodo.19207490>, 2015.
- International Energy Agency: Energy Sankey, <https://www.iea.org/data-and-statistics/data-tools/energy-sankey>, last access: 31 August 2026,
 2026.
- 395 Keen, A. and Blockley, E.: Investigating future changes in the volume budget of the Arctic sea ice in a coupled climate model, *The
 Cryosphere*, 12, 2855–2868, <https://doi.org/10.5194/tc-12-2855-2018>, 2018.
- Keen, A., Blockley, E., Bailey, D. A., Boldingh Debernard, J., Bushuk, M., Delhaye, S., Docquier, D., Feltham, D., Massonnet, F., O'Farrell,
 S., Ponsoni, L., Rodriguez, J. M., Schroeder, D., Swart, N., Toyoda, T., Tsujino, H., Vancoppenolle, M., and Wyser, K.: An inter-
 comparison of the mass budget of the Arctic sea ice in CMIP6 models, *The Cryosphere*, 15, 951–982, <https://doi.org/10.5194/tc-15->
 400 951-2021, 2021.
- Kennedy, A. B. W. and Sankey, H. R.: The thermal efficiency of steam engines, *Minutes of the Proceedings of the Institution of Civil
 Engineers*, 134, 278–312, <https://doi.org/10.1680/imotp.1898.19100>, 1898.
- Kuhlbrot, T., Jones, C. G., Sellar, A., Storkey, D., Blockley, E., Stringer, M., Hill, R., Graham, T., Ridley, J., Blaker, A., Calvert,
 D., Copsey, D., Ellis, R., Hewitt, H., Hyder, P., Ineson, S., Mulcahy, J., Siahaan, A., and Walton, J.: The low-resolution version of
 405 HadGEM3 GC3.1: development and evaluation for global climate, *Journal of Advances in Modeling Earth Systems*, 10, 2865–2888,
<https://doi.org/10.1029/2018MS001370>, 2018.
- Li, S., Huang, G., Li, X., Liu, J., and Fan, G.: An Assessment of the Antarctic Sea Ice Mass Budget Simulation in CMIP6 Historical
 Experiment, *Frontiers in Earth Science*, 9, 649 743, <https://doi.org/10.3389/feart.2021.649743>, 2021.
- Mankoff, K. D., Greene, C. A., Gardner, A. S., Davison, B., Treichler, D., Kochtitzky, W. H., Van Liefferinge, B., Wang, G., Ke, C.-Q.,
 410 Fettweis, X., Döhne, T., Fausto, R. S., and Ringeisen, D.: Ice sheet mass flow and balance with constituent terms 2010–19, *Journal of
 Glaciology*, 71, e131, 1–11, <https://doi.org/10.1017/jog.2025.10092>, 2025.
- Massonnet, F., Vancoppenolle, M., Goosse, H., Docquier, D., Fichet, T., and Blanchard-Wrigglesworth, E.: Arctic sea-ice change tied to
 its mean state across CMIP5 models, *Nature Climate Change*, 8, 599–603, <https://doi.org/10.1038/s41558-018-0204-z>, 2018.
- National Snow and Ice Data Center: NSIDC-0780: Arctic sea ice region mask, <https://doi.org/10.5067/CYW3O8ZUNIWC>, 2021.
- 415 Notz, D. and SIMIP Community: Arctic Sea Ice in CMIP6, *Geophysical Research Letters*, 47, e2019GL086 749,
<https://doi.org/10.1029/2019GL086749>, 2020.
- Notz, D. and Stroeve, J.: Observed Arctic sea-ice loss directly follows anthropogenic CO₂ emission, *Science*, 354, 747–750,
<https://doi.org/10.1126/science.aag2345>, 2016.
- Notz, D., Jahn, A., Holland, M., Hunke, E., Massonnet, F., Stroeve, J., Tremblay, B., and Vancoppenolle, M.: The CMIP6 Sea-Ice Model
 420 Intercomparison Project (SIMIP): understanding sea ice through climate-model simulations, *Geoscientific Model Development*, 9, 3427–
 3446, <https://doi.org/10.5194/gmd-9-3427-2016>, 2016.
- O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe,
 J., Meehl, G. A., Moss, R., Riahi, K., and Sanderson, B. M.: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6,
Geoscientific Model Development, 9, 3461–3482, <https://doi.org/10.5194/gmd-9-3461-2016>, 2016.



- 425 Parkinson, C. L.: A 40-y record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the Arctic, *Proceedings of the National Academy of Sciences*, 116, 14 414–14 423, <https://doi.org/10.1073/pnas.1906556116>, 2019.
- Petty, A., Cardinale, C., and Smith, M.: Constraining CMIP6 sea ice simulations with ICESat-2, *Geoscientific Model Development*, 18, 6313–6340, <https://doi.org/10.5194/gmd-18-6313-2025>, 2025.
- Plotly Technologies Inc.: plotly.py: The interactive graphing library for Python, <https://doi.org/10.5281/zenodo.14503524>, last access: 21
430 September 2026, 2015.
- Richaud, B., Massonnet, F., Fichefet, T., Topál, D., Barthélemy, A., and Docquier, D.: Anatomy of Arctic and Antarctic sea ice lows in an ocean–sea ice model, *The Cryosphere*, 20, 791–810, <https://doi.org/10.5194/tc-20-791-2026>, 2026a.
- Richaud, B., Massonnet, F., Fichefet, T., Topál, D., Barthélemy, A., and Docquier, D.: Ice mass fluxes for Anatomy of Arctic and Antarctic sea ice lows in an ocean–sea ice model, <https://doi.org/10.5281/zenodo.18347836>, 2026b.
- 435 Roach, L. A., Dörr, J., Holmes, C. R., Massonnet, F., Blockley, E. W., Notz, D., Rackow, T., Raphael, M. N., O’Farrell, S. P., Bailey, D. A., and Bitz, C. M.: Antarctic Sea Ice Area in CMIP6, *Geophysical Research Letters*, 47, e2019GL086729, <https://doi.org/10.1029/2019GL086729>, 2020.
- Rodgers, K. B., Lee, S.-S., Rosenbloom, N., Timmermann, A., Danabasoglu, G., Deser, C., Edwards, J., Kim, J.-E., Simpson, I. R., Stein, K., Stuecker, M. F., Yamaguchi, R., Chung, E.-S., Huang, L., Kim, W. M., Lamarque, J.-F., Lombardozzi, D. L., Wieder, W. R., and Yeager,
440 S. G.: Ubiquity of human-induced changes in climate variability, *Earth System Dynamics*, 12, 1393–1411, <https://doi.org/10.5194/esd-12-1393-2021>, 2021.
- Séférian, R., Nabat, P., Michou, M., Saint-Martin, D., Voldoire, A., Colin, J., Decharme, B., Delire, C., Berthet, S., Chevallier, M., Sénési, S., Franchisteguy, L., Vial, J., Mallet, M., Joetzjer, E., Geoffroy, O., Guérémy, J.-F., Moine, M.-P., Msadek, R., Ribes, A., Rocher, M., Roehrig, R., Salas-y Mélia, D., Sanchez, E., Terray, L., Valcke, S., Waldman, R., Aumont, O., Bopp, L., Deshayes, J., Éthé, C., and Madec,
445 G.: Evaluation of CNRM Earth System Model, CNRM-ESM2-1: Role of Earth system processes in present-day and future climate, *Journal of Advances in Modeling Earth Systems*, 11, 4182–4227, <https://doi.org/10.1029/2019MS001791>, 2019.
- Seland, Ø., Bentsen, M., Olivie, D., Toniazzo, T., Gjermundsen, A., Graff, L. S., Debernard, J. B., Gupta, A. K., He, Y.-C., Kirkevåg, A., Schwinger, J., Tjiputra, J., Aas, K. S., Bethke, I., Fan, Y., Griesfeller, J., Grini, A., Guo, C., Ilicak, M., Karset, I. H. H., Landgren, O., Liakka, J., Moseid, K. O., Nummelin, A., Spensberger, C., Tang, H., Zhang, Z., Heinze, C., Iversen, T., and Schulz, M.: Overview
450 of the Norwegian Earth System Model (NorESM2) and key climate response of CMIP6 DECK, historical, and scenario simulations, *Geoscientific Model Development*, 13, 6165–6200, <https://doi.org/10.5194/gmd-13-6165-2020>, 2020.
- Sellar, A. A., Jones, C. G., Mulcahy, J. P., Tang, Y., Yool, A., Wiltshire, A., O’Connor, F. M., Stringer, M., Hill, R., Palmieri, J., Woodward, S., de Mora, L., Kuhlbrodt, T., Rumbold, S. T., Kelley, D. I., Ellis, R., Johnson, C. E., Walton, J., Abraham, N. L., Andrews, M. B., Andrews, T., Archibald, A. T., Berthou, S., Burke, E., Blockley, E., Carslaw, K., Dalvi, M., Edwards, J., Folberth, G. A., Gedney, N.,
455 Griffiths, P. T., Harper, A. B., Hendry, M. A., Hewitt, A. J., Johnson, B., Jones, A., Jones, C. D., Keeble, J., Liddicoat, S., Morgenstern, O., Parker, R. J., Predoi, V., Robertson, E., Siahann, A., Smith, R. S., Swaminathan, R., Woodhouse, M. T., Zeng, G., and Zerroukat, M.: UKESM1: Description and evaluation of the U.K. Earth System Model, *Journal of Advances in Modeling Earth Systems*, 11, 4513–4558, <https://doi.org/10.1029/2019MS001739>, 2019.
- Vancoppenolle, M., Bouillon, S., Fichefet, T., Goosse, H., Lecomte, O., Morales Maqueda, M. A., and Madec, G.: LIM: The Louvain-la-
460 Neuve sea Ice Model, Tech. Rep. Note du Pôle de modélisation No. 31, Institut Pierre-Simon Laplace, ISSN 1288-1619, https://cmc.ipsl.fr/images/publications/scientific_notes/lim3_book.pdf, last access: 21 September 2026, 2012.



- Vancoppenolle, M., Rousset, C., Blockley, E., Aksenov, Y., Feltham, D., Fichefet, T., Garric, G., Guémas, V., Iovino, D., Keeley, S., Madec, G., Massonnet, F., Ridley, J., Schroeder, D., and Tietsche, S.: SI3, the NEMO Sea Ice Engine, <https://doi.org/10.5281/zenodo.7534900>, 2023.
- 465 Voldoire, A., Saint-Martin, D., Sénési, S., Decharme, B., Alias, A., Chevallier, M., Colin, J., Guérémy, J.-F., Michou, M., Moine, M.-P., Nabat, P., Roehrig, R., Salas y Mélia, D., Séférian, R., Valcke, S., Beau, I., Belamari, S., Berthet, S., Cassou, C., Cattiaux, J., Deshayes, J., Douville, H., Ethé, C., Franchistéguy, L., Geoffroy, O., Lévy, C., Madec, G., Meurdesoif, Y., Msadek, R., Ribes, A., Sanchez-Gomez, E., Terray, L., and Waldman, R.: Evaluation of CMIP6 DECK experiments with CNRM-CM6-1, *Journal of Advances in Modeling Earth Systems*, 11, 2177–2213, <https://doi.org/10.1029/2019MS001683>, 2019.
- 470 West, A., Collins, M., Blockley, E., Ridley, J., and Bodas-Salcedo, A.: Induced surface fluxes: a new framework for attributing Arctic sea ice volume balance biases to specific model errors, *The Cryosphere*, 13, 2001–2022, <https://doi.org/10.5194/tc-13-2001-2019>, 2019.
- West, A. E. and Blockley, E. W.: CMIP6 models overestimate sea ice melt, growth and conduction relative to ice mass balance buoy estimates, *Geoscientific Model Development*, 18, 3041–3064, <https://doi.org/10.5194/gmd-18-3041-2025>, 2025.
- Yukimoto, S., Kawai, H., Koshiro, T., Oshima, N., Yoshida, K., Urakawa, S., Tsujino, H., Deushi, M., Tanaka, T., Hosaka, M., Yabu, S.,
- 475 Yoshimura, H., Shindo, E., Mizuta, R., Obata, A., Adachi, Y., and Ishii, M.: The Meteorological Research Institute Earth System Model Version 2.0, MRI-ESM2.0: Description and basic evaluation of the physical component, *Journal of the Meteorological Society of Japan*, 97, 931–965, <https://doi.org/10.2151/jmsj.2019-051>, 2019.